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CARBON-PHENOLIC CAGES FOR HIGH-SPEED BEARINGS

Part I - Friction and Wear Response of Phenolic Composite Impregnated with a Multiply-Alkylated Cyclopentane (MAC) Lubricant and MoS_2 Solid Lubricant

Nelson H. Forster

Mechanical Systems Branch (AFRL/PRTM)
Turbine Engine Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

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PROPULSION DIRECTORATE
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WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

NOTICE

This technical report has been reviewed and is approved for publication.

NELSON H. FORSTER, Ph.D.
Principal Mechanical Engineer
Mechanical Systems Branch

ROBERT L. WRIGHT, Ph.D.
Chief, Mechanical Systems Branch

THEODORE G. FECKE
Chief Engineer
Turbine Engine Division
Propulsion Directorate

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14. ABSTRACT ***(Maximum 200 Words)***
This is the first part of a three-part series of reports by AFRL/PRTM to investigate carbon-phenolic bearing cages in high-speed, lightly lubricated bearings. This portion covers characterization of flat panel specimens using thermal conductivity, tensile strength, coefficient of thermal expansion measurements, and friction and wear testing in a sliding contact. The experimental data indicate that the carbon-phenolic has superior mechanical and thermal properties to the cotton-phenolic material. The friction and wear properties were similar to the cotton-phenolic baseline.

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1. Introduction

The objective of this effort was to develop a new bearing cage material made from a carbon fiber-phenolic resin matrix (carbon-phenolic), with the end goal of producing a material that would have better performance than cotton-phenolic cages in high-speed, lightly lubricated bearings. This is the first part of a three-part series of reports. This report addresses the initial material selection, mechanical and thermal characterization, and tribology testing. Part II covers the experimental bearing testing, and Part III covers thermal modeling of the bearing. There are also a set of reports in progress from the Air Force Research Laboratory Materials Directorate that address testing in vacuum and hard coatings on the bearing steel.

The rationale for selecting carbon-phenolic candidate material was based on the potential to significantly improve the mechanical and thermal properties of the cotton phenolic material. Based on prior experience with carbon matrix - carbon fiber cages (C-C) [1 2], we anticipated that replacing cotton fibers with carbon fibers would greatly improve the thermal conductivity, strength, and modulus of elasticity, while also decreasing the coefficient of thermal expansion. Additionally, there would be less cost in fabricating carbon-phenolic cages compared to C-C cages, since producing the matrix is a primary cost driver of producing C-C composite material. We also hoped to lower the coefficient of friction (COF) of the carbon-phenolic matrix by incorporating lubricants into the matrix of the cage. The following lubricants were used for this purpose; the multiply, alkylated, cyclo-pentane (MAC) liquid lubricant commercially known as Pennzane®, powdered molybdenum disulfide (MoS_2), and powdered fluorinated graphite (CF). Ideally, if we could develop a carbon-phenolic material with equivalent or lower friction than the standard cotton-phenolic material and improved mechanical and thermal properties, we would have a better bearing cage material than the cotton-phenolic material used today. The material would also provide a lower cost cage than C-C with many of the same performance benefits.

2. Experimental

2.1 Material Samples

Flat panel specimens were generated at the beginning of the program to characterize the material properties. Allcomp Inc., City of Industry, California supplied all of the test specimens. The particular specimens used in the study are listed in Table 1. The specimen numbers, 10818 through 10827, are used to identify the specimens throughout the report. A photograph of a typical friction and wear specimen is shown in Figure 1. Each sample was 2.00 inches long by 0.50 inch wide by 0.25 inch thick. The shiny spot on the sample is a wear scar after a single test. All of the samples essentially had the same appearance and dimensions. All of the panels were produced with a T300 3k carbon fiber matt. The matt had an 8-harness satin weave with 24/23 tows/inch fabric. All of the samples were cured at 450°F for 12 hours. Specimens 10819 and 10827 had an additional postcure cycle to further stabilize the phenolic resin and intentionally open up some additional open-pore porosity.

In specimens 10822 and 10823 the CF lubricant was included into the resin matrix. The CF 3000 is an Atlantic Research Chemical, Inc. (ARC) product converted from 2-micron graphite and containing 60.4 percent fluoride. The CF 4000 is an ARC product converted from 6-micron graphite and containing 64.2 % fluoride. As stated in Table 1, specimens 10824, 10825, and 10826 had powdered MoS_2 incorporated into the matrix at a concentration of 5, 10, and 20 % by weight, respectively. The MoS_2 was obtained from Atlantic Equipment Engineers, Catalog No. MO-801, and is reported to be 99.8% pure with a range in particle size of 1 to 5 microns.

To characterize the material properties, the samples were tested under tension for modulus of elasticity and tensile strength. This testing was performed by Materials Innovation, Inc. per ASTM D 3039. The tensile testing was performed only in the in-plane direction. This is the plane of highest concern in bearing cages for tensile strength and modulus, and typically the fiber matt is wrapped circumferentially to optimize the part for hoop characteristics. However, interlaminar shear strength can also be a critical parameter in high-speed bearings, particularly those made with 2-D fiber weaves, wrapped in the manner described above. Due to the limited funds and scope of this program, the interlaminar shear strength was not measured. The thermal conductivity was measured by Dr. Hasslemann of Virginia Polytechnic Institute using laser flash thermal diffusivity. Thermal conductivity was measured in both the in-plane direction and normal to the fiber weave.

In preparation of the friction and wear testing, most of the specimens were vacuum impregnated with a MAC lubricant, commercially known as Pennzane®. The impregnation of the lubricant was performed by AFRL/MLBT and a description of that process is covered in a separate report.

Table 1. Carbon-Phenolic Composite Specimens

Specimen Number	Sample Preparation
10818	T300/Phenolic (No filler, as cured)
10819	T300/Phenolic (no filler, Fast cycle postcured)
10827	T300/Phenolic (no filler, long cycle postcured)
10822	T300/phenolic (CF300 10% wt. In matrix, as cured)
10823	T300/phenolic (CF 4000 10% wt. In matrix, as cured)
10824	T300/Phenolic (MoS_2 5% wt. In matrix, as cured)
10825	T300/Phenolic (MoS_2 10% wt. In matrix, as cured)
10826	T300/Phenolic (MoS_2 20% wt. In matrix, as cured)

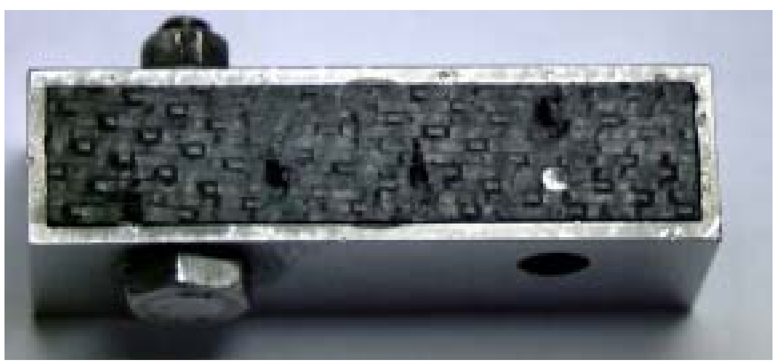

Figure 1. Example of a Carbon-Phenolic Sample in the Test Holder

2.2 Friction and Wear Testing

A cross section of the friction and wear tester used to characterize the specimens is shown in Figure 2. For these tests, the rotating disk was replaced with a dead weight holder that contained the samples shown in Figure 1. The tester has a 1.125-inch ball mounted on a shaft and can be driven at speeds up to 21,000 rpm. In the test, the friction and wear samples were dead weight loaded against the rotating ball. Friction testing was performed at a normal load of 2.0 N (0.45 lb) and at 3.5 N (0.79 lb). Testing was performed at 5, 10, and 15 m/s ball surface speed. For the 206 bearing used in Part II, the 5, 10, and 15 ms are the pitch line speed (essentially the cage land sliding speed) at bearing shaft rpm of 4,616, 9,232, and 13,847. Most of the bearing speed data in Part II was performed between 10,000 and 20,000 rpm, so the friction data obtained here provides a good estimation of the bearing friction for analysis in Part III. A thermocouple placed lightly in contact with the rotating ball was used to record the ball temperature. A torque sensor in line with the ball shaft was used to measure the ball torque and calculate the resultant friction coefficient. All of the testing was done in air environment, and the relative humidity was measured and recorded at the beginning of each test. Most of the tests ran for a duration of 15 minutes. Additionally some of the tests ran for a period of 3 hours on one spot to measure long-term effects.

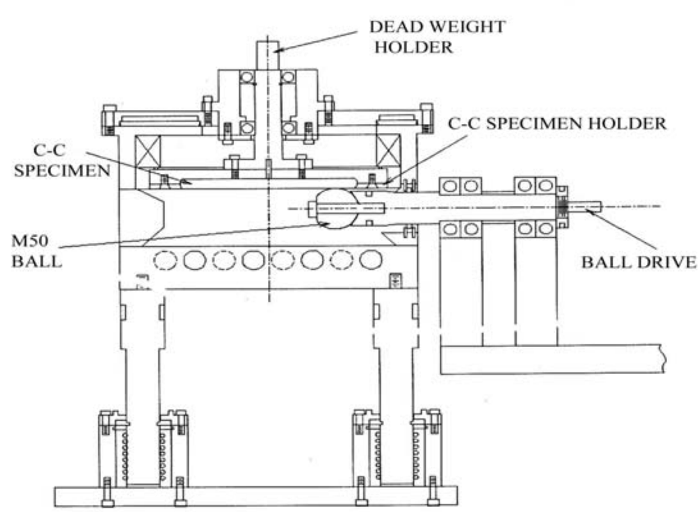

Figure 2. Cross Section of the Optical EHD Test Rig Used for the Friction and Wear Testing

3. Experimental Results

3.1 Material Samples

Values for the mechanical and thermal properties from specimens 10818 (no filler, as cured), 10825 (10 % by weight MoS_2, as cured), and a cotton-phenolic baseline material are shown in Table 2. The cotton-phenolic values were taken from the internet site www.efunda.com . As seen in Table 2, the modulus in the fiber direction is much higher with carbon fibers than cotton fibers. A higher modulus is beneficial in reducing growth from centrifugal stress in high-speed bearings. Also shown is the coefficient of thermal expansion (COTE). There is also a very large difference in the COTE, with the carbon-phenolic being much lower than the cotton-phenolic material. Similar to modulus, a low COTE will reduce growth of the cage in operation. A material with a high modulus and low COTE will be very stable at high speed, and if designed as an outer land riding cage, will essentially eliminate thermal runaway of the bearing cage.

Table 2 - Mechanical and Thermal Properties of Carbon-Phenolic and Cotton-Phenolic

	Cotton-Phenolic	Carbon-Phenolic	Carbon-Phenolic (10% MoS_2)
Modulus - xy (GPa)	7.6 - 9.7	62.3	56.1
CTE - xy (10^{-6} / ^{o}C)	15 - 22 ……………… ………………..	0.7	0.9
T Strength -xy (MPa)	41-69	637	652
k - z (W/m-K)	0.33 – 0.42	0.85	0.80
k - xy (W/m-K)	0.33 – 0.42	3.25	2.10
Density (g/cm^3)	1.30 – 1.42	1.40	

3.2 Friction and Wear Testing

A baseline test of a cotton-phenolic material, with and without the Pennzane® lubricant, is shown in Figure 3. At the higher load, the COF without liquid lubricant is erratic and reaches values in excess of 1.75 for short duration. At the lower load of 2 N, the material is better behaved without the liquid lubrication, but the friction is still very high. Clearly, the cotton-phenolic material does not perform well in sliding contacts without a lubricant. Also shown in Figure 3 is a plot for the cotton-phenolic material impregnated with the Pennzane® lubricant. The COF is a steady value of about 0.18. The wear scar for the lubricated condition was much smaller when the lubricant was present. While the COF is much lower with the liquid lubricant, it is not as low as would normally be expected with a liquid lubricant.

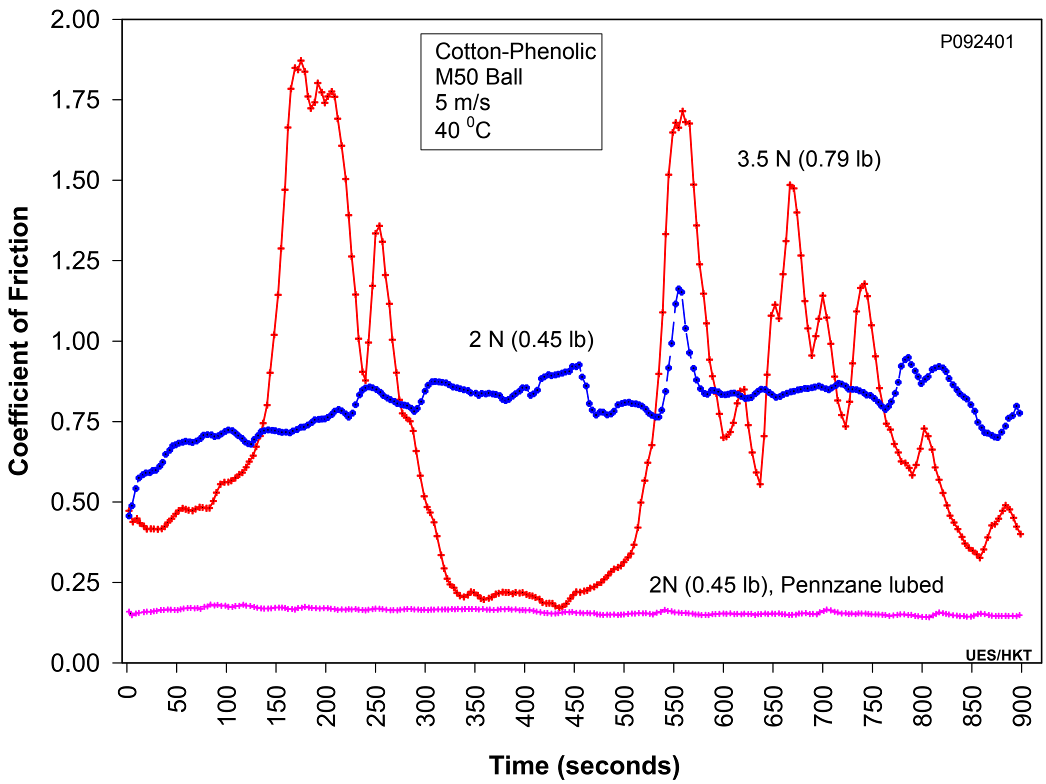

Figure 3. Friction Data for the Cotton-Phenolic Material with and Without the Pennzane® Lubricant

The carbon-phenolic material without the liquid lubricant is shown in Figure 4. Results are shown for sample 10818 (as cured) and 10826 (as cured with MoS_2). At start up, both samples perform better than the unlubricated cotton-phenolic, but the friction is still high for a tribo-contact where low friction is desired. With time, the sample without MoS_2 reaches a very high friction coefficient similar to the cotton- phenolic sample. Ball temperature plots corresponding to Figure 4 are shown in Figure 5. As expected, the ball temperature responds closely to the measured friction coefficient, reaching a temperature as high as 135°C with the unlubricated specimen. It should also be considered that the localized contact spot on the stationary composite specimen would be at much higher temperature than the rotating ball. The very high COF in the lubricated specimens is probably due in part to this temperature and micro seizure in the contact. In the notes on the figure, WS refers to the wear scar diameter and RH to the relative humidity measured on that particular day in the test cell.

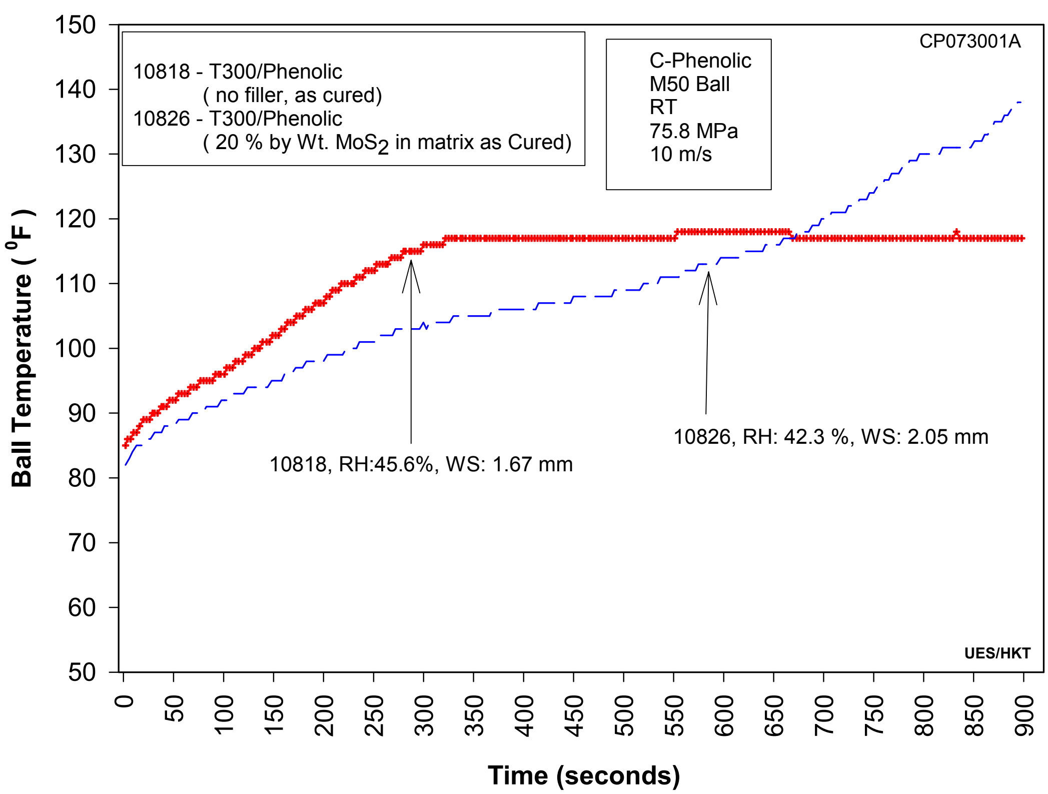

Figure 4. Friction of Carbon-Phenolic Dry and with 20% by Weight MoS_2 at 10 m/s Sliding Speed

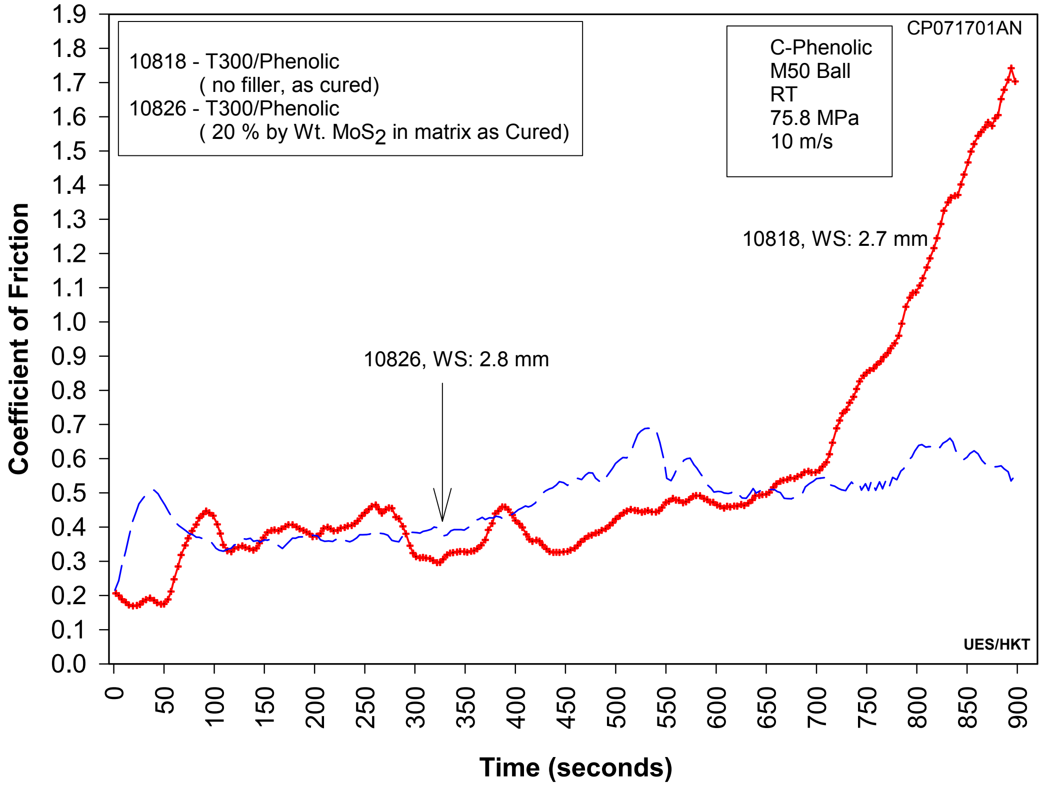

Figure 5. Ball Temperature of the Carbon-Phenolic Sample with and without MoS_2 at 10 m/s Sliding Speed

A comparison of the COF of cotton-phenolic and the three carbon-phenolic samples impregnated with the Pennzane® fluid, 108818, 10819, and 10827, is shown in Figure 6. All of the tests in Figure 6 are for a sliding speed of 5 m/s. Two of the samples, 10819 and 10827, show close agreement with the cotton-phenolic specimen at a value of about 0.17. One of the carbon-phenolic specimens, 10818, has a higher COF. The wear scar was fairly low in all four cases, as noted on the figure.

Friction data at 10 m/s for the cotton phenolic and samples 10818, 10819, and 10827 is shown in Figure 7. In this case, samples 10818 and 10827 show close agreement with the cotton-phenolic sample at a value of about 0.20, and sample 10819 is lower.

Friction data at 15 m/s for the cotton-phenolic and samples 10818, 10819, 10827 is shown in Figure 8. All of the carbon-phenolic specimens are higher than the cotton-phenolic and range from 0.20 to 0.26.

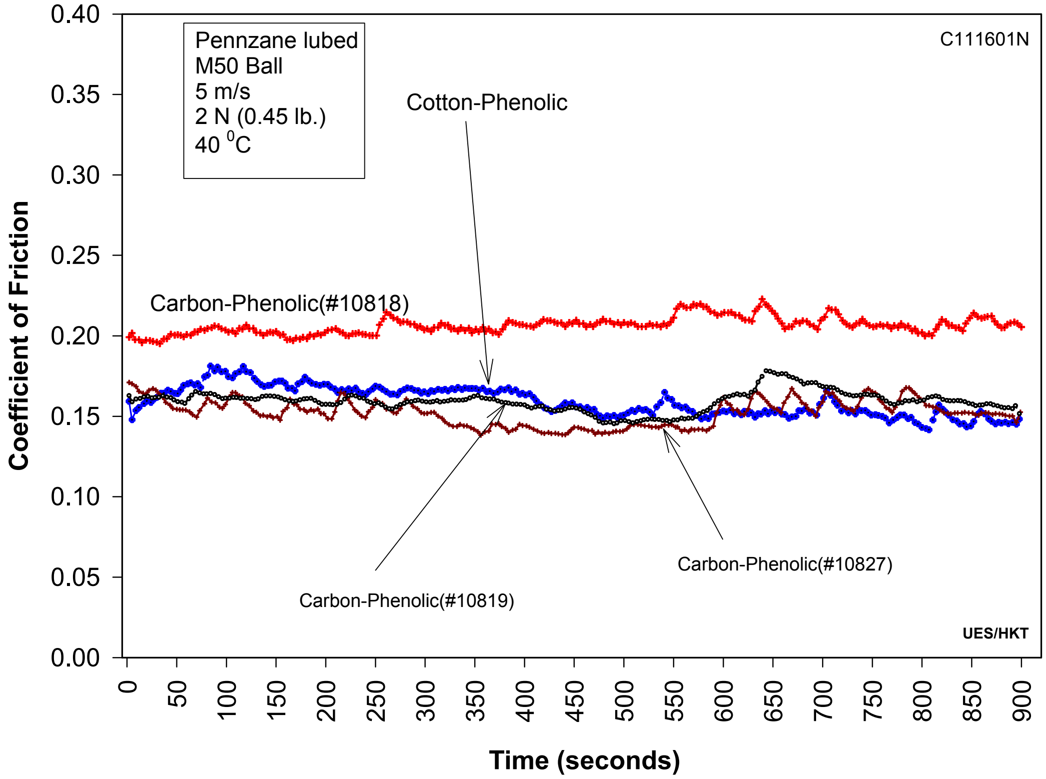

Figure 6. COF of Cotton-Phenolic and Carbon-Phenolic with Pennzane® Lubricant at 5 m/s Sliding Speed

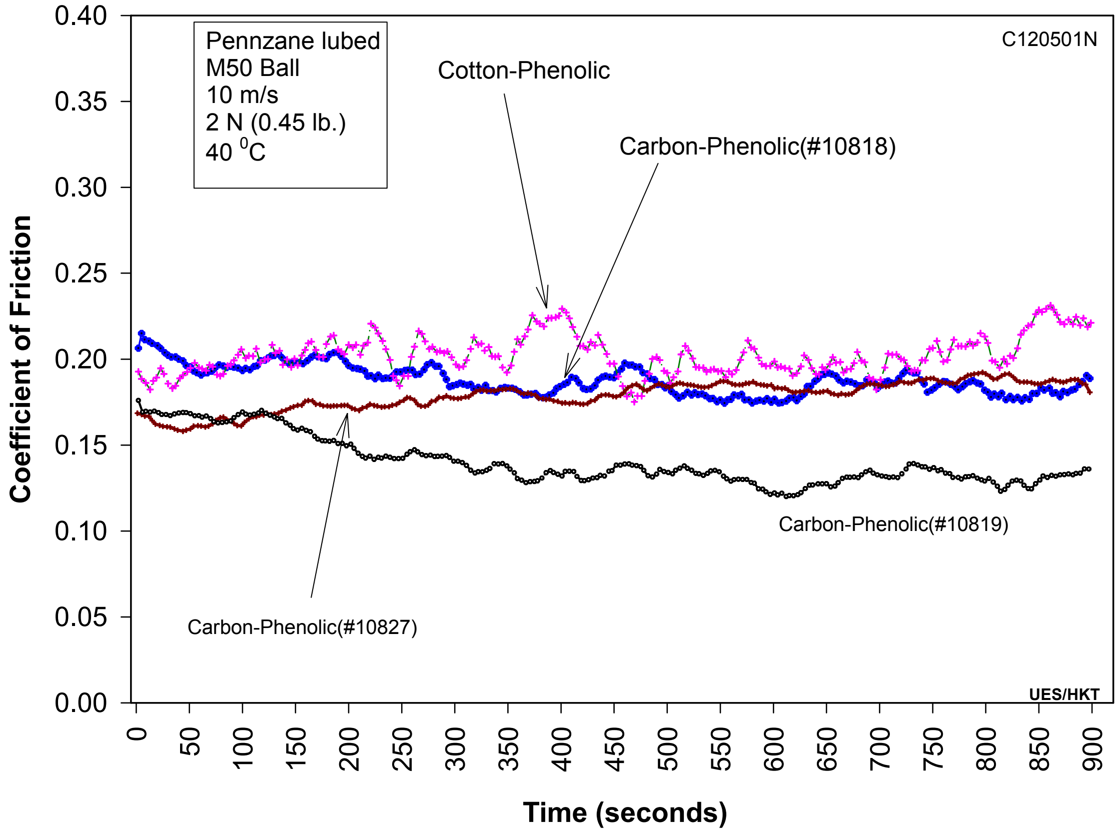

Figure 7. COF of Cotton-Phenolic and Carbon-Phenolic with Pennzane® Lubricant at 10 m/s Sliding Speed

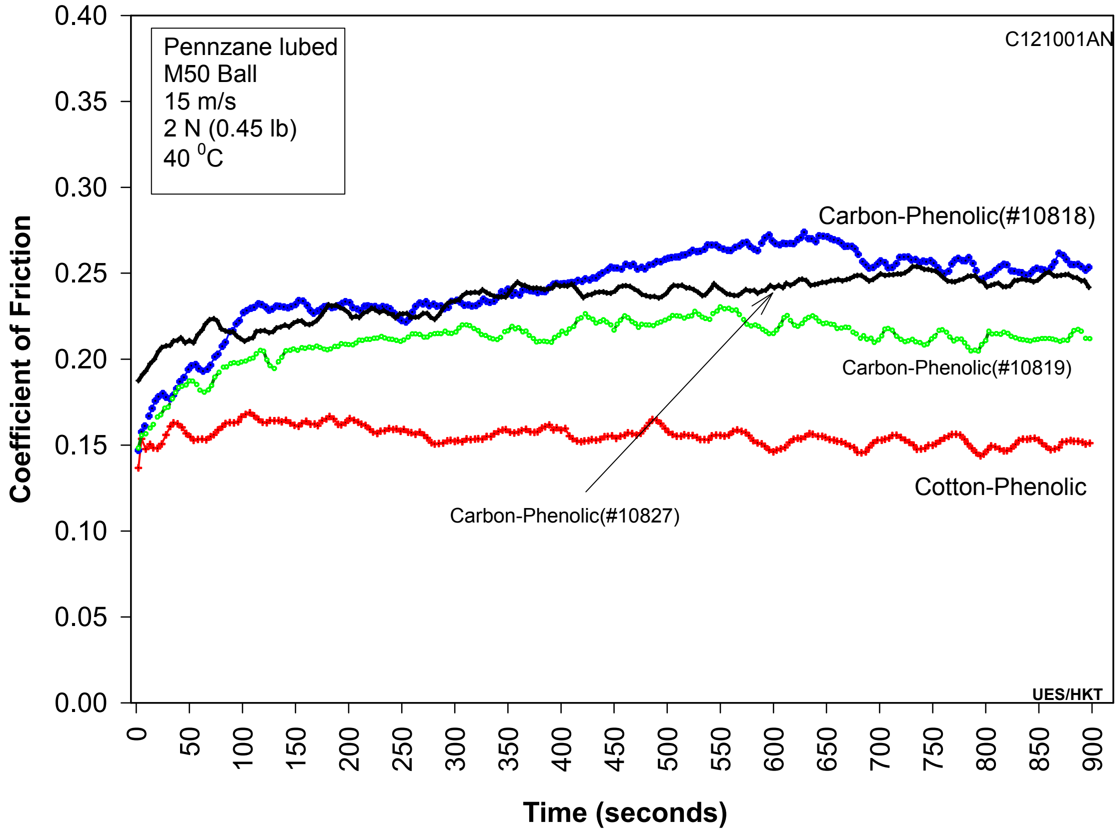

Figure 8. COF of Cotton-Phenolic and Carbon-Phenolic with the Pennzane® Lubricant at 15 m/s Sliding Speed

Results for the 3-hour tests with cotton-phenolic and carbon-phenolic are shown in Figure 9. Similar to the other tests, there is agreement between most of the samples but not all. In this case, carbon-phenolic specimens 10818 and 10827 ran at a COF of 0.18. The test with the cotton-phenolic ran at a COF ranging from 0.15 to 0.25 and seemed to increase with time. There was one carbon-phenolic test from sample 10819 that reached a relatively low friction of 0.05 but did not stay there. That sample ended up at a COF of about 0.13.

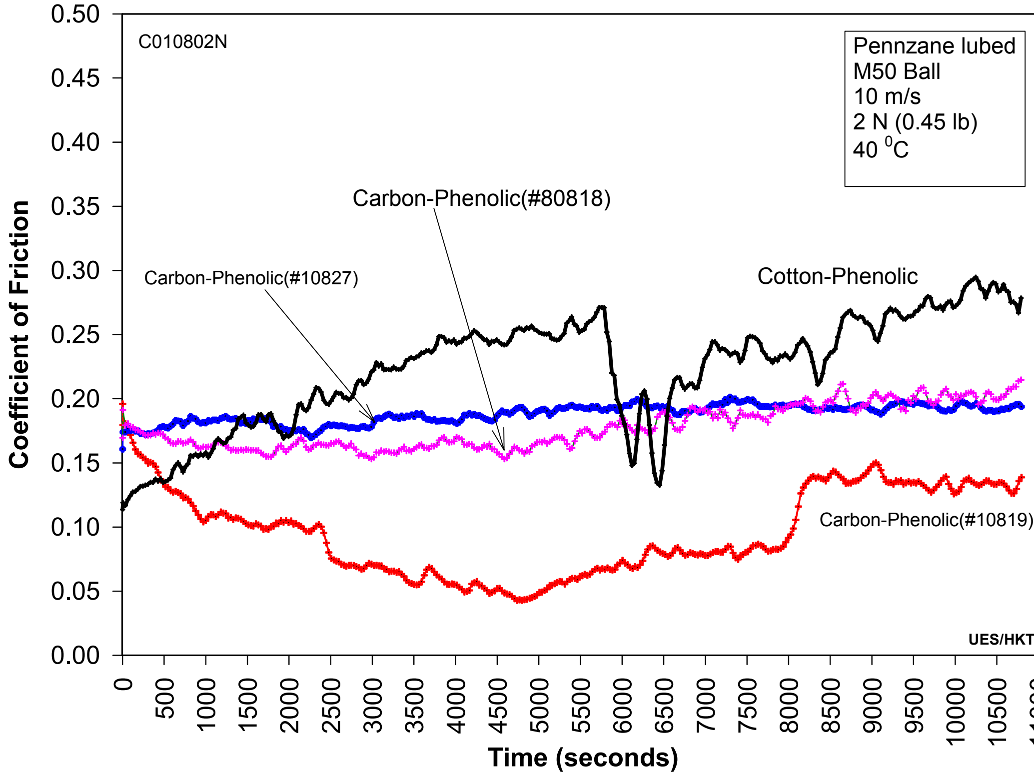

Figure 9. Comparison the Carbon-Phenolic and Cotton-Phenolic in a 3-Hour Sliding Test with the Pennzane® Lubricant

4. Conclusions

The strength, thermal conductivity, and COTE of carbon-phenolic samples are superior to cotton-phenolic. These three properties are particularly important for high-speed bearings, suggesting that the carbon-phenolic cages will perform better in high-speed bearings. In Part III, the thermal modeling uses the data from Part I to assess some of the potential benefits.

In general, the COF of several carbon-phenolic samples and a cotton-phenolic baseline material were similar under similar test conditions. This suggests that the phenolic matrix of the material has a dominant affect. This is probably due to the open porosity of the phenolic material.

The MoS_2 in sample 10826 may have a slight beneficial effect, but the results were not conclusive and not sufficient to be considered a low friction material. The results here suggest that solid lubricants blended in a resin matrix of carbon-phenolic is not a particularly effective means for improving the friction and wear response.

The best performance with different lubricants was with the Pennzane® impregnated in the composites. This produces a COF between 0.15 and 0.25 under most conditions. While these values are much better than the dry phenolic samples or the samples where solid lubricants have been blended in the matrix, they are still higher than what would be expected with a liquid lubricant. At this time, this is attributed to the porous nature of the composite materials which inhibits the formation of the traditional hydrodynamic film. Additional studies are underway to confirm this hypothesis.

5. References

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2. Brown, J.R. and Forster, N.H., “Numerical Investigation of the Effect of Carbon-carbon Composite Cages on High-Speed Bearing Operating Temperatures,” 45, 3, pp. 411-417 (2002).